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Meteoroid Environment Near the Earth-Moon System

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Final Technical Report

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FOREWORD

We undertook a research program to investigate the properties of small objects crossing the orbit of the Earth-Moon system using a unique set of data obtained during the Apollo lunar landing missions with a network of seismic stations on the the surface of the Moon. The primary objectives of the study were to find out the nature of these objects, whether they were of cometary or asteroidal origin based on their orbital distributions and seismic effects upon impacts, and then to infer the role these small objects play in the evolution of the solar system. In this final technical report, we briefly summarize the results of this study. Detailed results of the study have been published in a series of papers and a dissertation, which are listed in the PUBLICATIONS section. Abstracts of the published papers and the dissertation are attached as an appendix.

SUMMARY OF RESULTS

The large number of impact events detected by the network of seismic stations on the Moon allowed us to apply various statistical methods to infer the pre-impact orbital parameters of groups of meteoroids even though such parameters cannot be obtained for a single impact using seismic signals alone. The distribution of impact events in the time-of-year space, representing the orbital location, and that in the time-of-day space, representing the orbital direction, are found to contain significant amount of nonrandom components, indicating that many small objects in the Earth-crossing orbits occur in clusters. Furthermore, a distinct difference in distribution found between smaller objects (estimated mass less than about 1 kg) and larger objects (estimated mass greater than about 1 kg) manifests that they represent different classes of objects.

The orbital parameters inferred from the distribution of most small objects coincide with those of known meteor showers, which are believe to originate from long-period comets. Thus, they are likely to be mostly cometary fragments. In contrast, the larger objects show little correlation with meteor showers, and furthermore their orbits as inferred from their distribution are mostly retrograde. Thus, they are likely to be derived from Earth-crossing asteroids and shot-period comments.

Overall, 28% of the smaller impacts and 15% of the larger impacts are found to occur in clusters. Since their orbits closely follow the orbits of their parent bodies, this implies that significant number of comets and asteroids is in Earth-crossing orbits. The remainder of the impacting objects have their orbits randomized, and thus the orbits of their parent bodies could not be inferred.

Some larger objects are found to occur in swarms, suggesting that they left their parent body relatively recently. One such swarm may be associated with a known meteorite. If true, some meteorites are indeed derived from Earth-crossing asteroids.

The above results lead to the following scenario for the origin of these small objects now in Earth-crossing orbits. There are primarily two dissimilar types of meteoroidal objects now in the inner solar system: cometary and asteroidal.

It is believed that more than 10^{11} comets are in a so-called Oort cloud located 10^4 to 10^5 AU from the Sun. Occasionally, the orbits of some comets are disturbed by a passing star, and they enter the solar system. Further perturbation by the major planets put them into Earth-crossing orbits. Disintegration of these comments as they approach the Sun produces a swarm, and then a stream of small cometary objects, which are observed as meteor showers on the Earth. These mostly icy objects are too friable to survive the entry through the earth's atmosphere, but since the Moon has little atmosphere their impacts on the lunar surface are detected as they generate weak seismic waves.

Asteroidal objects are of entirely different origin. Although most asteroids are in the main asteroidal belt, which is located between the orbits of Mars and Jupiter, there are groups of asteroids whose orbits cross the orbit of the Earth-Moon system. Occasionally, a collision with another asteroid causes one of them to break up, forming a swarm of small asteroidal objects in Earth-crossing orbits. In time, the perturbation by the planets randomize the orbits of these objects, and when they fall on the Earth, they are observed as sporadic meteors. However, those deriving from relatively recent break up retain the orbit of their parent body. These objects are much more coherent than the cometary objects, and some of them survive the atmospheric entry and are collected as meteorites.

REMAINING PROBLEMS

Corollary to this study is the determination of the flux density of meteoroids in the Earth-crossing orbits. This is not straightforward because there are several problems that need be examined in detail. Among them is the efficiency of seismic wave generation upon impact as a function of density of impacting object. We are currently working to solve these problems using the available set of data.

Because of the limitation in funding for this research, we were able to use only about 1700 impact events detected by the long-period seismometers for this study. Those detected by the short-period seismometers only, representing smaller impacts, has not yet been analyzed. They are several times larger in number than the long-period events and were spread out in about 7000 computer tapes. We have recently copied these data onto about 40 8-mm video tapes. Thus, the processing and analysis of these data are now expected to be much more manageable than was possible before.

PUBLICATIONS

(Some related publications before the funding start are also included for completeness)

Published Papers

Oberst, J. and Y. Nakamura, Distinct meteoroid families identified on the lunar seismograms, *Proc. Lunar Planet. Sci. Conf. 17th, J. Geophys. Res., 92 (B4)*, E769-E773, 1987.

Oberst, J. and Y. Nakamura, Monte Carlo simulation of the diurnal variation in seismic detection rate of sporadic meteoroid impacts on the Moon, *Proc. Lunar Planet. Sci. Conf., 19th*, 615-625, 1989.

Oberst, J., Possible relationship between the Farmington meteorite and a seismically detected swarm of meteoroids impacting the Moon, *Meteoritics 24*, 23-28, 1989.

Oberst, J. and Y. Nakamura, Search for clustering among the meteoroid impacts detected by the Apollo lunar seismic network, *Icarus, 91*, 315-325, 1991.

Papers in Preparation

Oberst, J. and Y. Nakamura, A new estimate of the meteoroid flux on the lunar surface from seismic data, to be submitted to *Meteoritics*.

Dissertation

Oberst, P. J., Meteoroids near the Earth-Moon system as inferred from temporal and spatial distribution of impacts detected by the lunar seismic network, Ph. D. dissertation, Univ. of Texas at Austin, x+135 pp, May 1989.

Oral Presentations and Abstracts

Oberst, J. and Y. Nakamura, Preliminary identification of different meteoroid families impacting the lunar surface, *17th Lunar Planet. Sci. Conf.*, Houston, March 1986; *Lunar Planet. Sci., XVII* 628-629, 1986

Oberst, J., On the stability of "meteorite swarms' in resonant orbits — A preliminary study, *18th Lunar Planet. Sci. Conf.*, Houston, March 1987; *Lunar Planet. Sci., XVIIII*, 734-735, 1987.

Oberst, J. and Y. Nakamura, Lunar seismic impact clusters — Evidence for the presence of "meteorite streams"; *18th Lunar Planet. Sci. Conf.*, Houston, March 1987; *Lunar Planet. Sci., XVIIII*, 736-737, 1987.

Oberst, J. and Y. Nakamura, Is the Farmington meteorite a sample from a comet?, *Am. Geophys. Union Fall Meeting*, San Francisco, December 1986; *EOS Trans. Am. Geophys. Union, 67*, 1071-1072, 1986.

Oberst, J. and Y. Nakamura, Updated lunar seismic meteoroid flux, *Am. Geophys. Union Spring Meeting*, Baltimore, May 1997; *EOS Trans. Am. Geophys. Union, 68*, 344, 1987.

Oberst, J. and Y. Nakamura, A Monte Carlo simulation of the diurnal variation in seismic detection rate of sporadic lunar meteoroid impacts, *19th Lunar Planet. Sci. Conf.*, Houston, March 1988; *Lunar Planet. Sci., XIX*, 879-890, 1988.

Oberst, J. and Y. Nakamura, A seismic risk for the lunar base, *Symposium on Lunar Bases and Space Activities in the 21st century*, Houston, April 1988.

Oberst, J. and Y. Nakamura, A new estimate of the meteoroid impact flux on the Moon, *20th Lunar Planet. Sci. Conf.*, Houston, March 1989; *Lunar Planet. Sci., XX*, 802-803, 1989.

Oberst, J. and Y. Nakamura, Estimating source locations when accurate arrival times are not available, *Seismol. Soc. Am. Ann. Meeting*, April 1989; *Seismol. Res. Lett., 60*, 31, 1989.

Oberst, J. and Y. Nakamura, Temporal and spatial distribution of meteoroid impacts detected by the lunar seismic network — *A summary report, Conf. on Asteroids, Comets, Meteors III*, Uppsala, June 1989.

APPENDIX

Abstracts of published papers and dissertation

PROCEEDINGS OF THE SEVENTEENTH LUNAR AND PLANETARY SCIENCE CONFERENCE, PART 2
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 92, NO. B4, PAGES E769–E773, MARCH 30, 1987

Distinct Meteoroid Families Identified on the Lunar Seismograms

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We reexamined the seismic events originating from impacts of meteoroids on the lunar surface, as recorded by the Apollo lunar seismic network, in terms of (1) difference in temporal distribution between large and small impacts, (2) clustering of impacts in a two-dimensional space of the time of the year and the time of the month (lunar day), and (3) their relationship with terrestrial observations. The study led us to identify several distinct families of meteoroids impacting the moon. Most meteoroids producing small impact-seismic events appear to approach from retrograde heliocentric orbits, including many that are associated with well-known cometary showers. In contrast, most meteoroids associated with large impact-seismic events appear to approach from prograde orbits. Although some of them may also be cometary, the observation is consistent with a hypothesis that many of them represent stony asteroidal material. A unique cluster of large-amplitude impact events observed in June, 1975, appears to be associated with the Taurid cometary complex, suggesting that the Taurids contain more massive or even denser objects than other meteor showers. The previously reported discrepancy between lunar and terrestrial meteoroid-flux estimates may be due to the differences in

Proceedings of the 19th Lunar and Planetary Science Conference, pp. 615-625

Monte Carlo Simulations of the Diurnal Variation in Seismic Detection Rate of Sporadic Meteoroid Impacts on the Moon

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The rate of detection of meteoroid impacts on the Moon by the lunar seismic network shows a characteristic diurnal variation. Assuming that these meteoroids have a flux and a preimpact orbital distribution similar to that of fireballs observed by terrestrial camera networks, one can compute the expected diurnal variation for a given set of parameters that describe the seismic wave generation and transmission on the Moon. An iterative process to match the theoretical variation with the observed one has led us to the following results: (1) The majority of the detected impact events occur within a closer range of the network than was believed earlier. This results in higher meteoroid flux estimates from lunar seismic data that agree with the terrestrially measured flux. (2) For meteoroid masses smaller than 1000 g, seismic amplitude is approximately proportional to the one-fifth power of the impact speed; for larger masses it is approximately proportional to the eight-fifth power, provided that the terrestrial meteor data used for analysis are not biased. (3) Seismic efficiency of meteoroids smaller than 1000 g is significantly less than that of large meteoroids. (4) Using orbits of fireballs that represent meteorites, we predict that the share of meteorites among the detected impacts is approximately 15% assuming that seismic efficiency of the high-density meteorites is the same as that of average meteoroids. A greatly increased seismic efficiency for these high-density objects is not likely.

Meteoritics 24, 23–28 (1989)

Possible relationship between the Farmington meteorite and a seismically detected swarm of meteoroids impacting the Moon

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(*Received 14 October 1988; accepted in revised form 7 February 1989*)

Abstract—The Farmington ordinary L5 chondrite with its uniquely short cosmic-ray exposure age of less than 25 000 years may have been a member of a large meteoroid swarm which was detected by the Apollo seismic network when it encountered the Moon in June 1975. The association implies that the parent body of the Farmington meteorite was in an Earth-crossing orbit at the time the swarm was formed. This supports the idea that at least some meteorites are derived from the observable population of Earth-crossing asteroids.

ICARUS **91**, 315–325 (1991)

A Search for Clustering among the Meteoroid Impacts Detected by the Apollo Lunar Seismic Network

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Received April 23, 1990; revised February 6, 1991

We examined temporal clustering of meteoroid impacts detected by the Apollo lunar seismic network and found a distinct difference between "small" meteoroids (masses smaller than about 1 kg) and "large" meteoroids (masses larger than about 1 kg). Small meteoroids show strong clustering, many of which are identified with showers known from terrestrial meteor studies. In contrast, little clustering is found for large meteoroids, suggesting that they represent meteoroids of type and origin different from those of the small meteoroids. Overall, 28% of the small events and 15% of the large events occur as clusters. The small meteoroids appear to be mostly cometary, while the large meteoroids may be derived from near-Earth asteroids and short-period comets. Two swarms of large meteoroids detected in June 1975 and January 1977 possibly contain high-density meteoritic objects, and thus may represent "meteorite streams."

METEOROIDS NEAR THE EARTH-MOON SYSTEM AS INFERRED FROM TEMPORAL AND SPATIAL DISTRIBUTION OF IMPACTS DETECTED BY THE LUNAR SEISMIC NETWORK

Publication No. __________

Peter Jürgen Oberst, Ph.D.
The University of Texas at Austin, 1989
Supervising Professor: Yosio Nakamura

The meteoroid impacts detected by the lunar seismic station network are examined in terms of a) the distribution of impact locations and energies, b) the diurnal variation of impact rate, and c) temporal clustering. Small meteoroids (estimated masses smaller than 1 kg) and large meteoroids (estimated masses larger than 1 kg) are found to differ significantly in their temporal distributions. Small meteoroids show strong clustering. Several known cometary showers are identified among the clusters; the Perseids, Leonids, Aquarids, Orionids, and Geminids being the most prominent. The majority of the detected objects approaches at high speeds from highly inclined orbits. In contrast, large meteoroids travel predominantly in orbits of low inclination and show little clustering. The average impact flux of these large objects is estimated to be $\log_{10} n(E) = -0.99 \log_{10} E + 11.38$ for the energy range 2×10^{11} J to 2×10^{12} J, where n is the cumulative number of meteoroids having kinetic energies greater than E, in Joule, impacting the lunar surface. This agrees within a factor of five with flux rates of terrestrially observed "airwave objects"

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(very large meteoroids) and flux rates estimated from lunar crater statistics. Sources of the small-mass meteoroids are suggested to be mostly long-period comets. The diurnal distribution of the detected large-mass meteoroids indicates that most of them do not represent high-density meteorites but low-density material too fragile to survive the terrestrial atmospheric entry. These large objects are probably derived from short-period comets and the low-density members among the near-Earth asteroids.